PATENT APPLICATION FOR
"APPARATUS AND METHODS FOR USING FIBER OPTIC ARRAYS IN OPTICAL COMMUNICATION SYSTEMS"

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FIELD OF THE INVENTION

The present invention relates generally to optical communications, and more particularly to fiber optic communication systems.

BACKGROUND OF THE INVENTION

Optical communication technologies are employed in a wide variety of communication environments. Examples of such communication environments include, but are not limited to, telecommunications, networking, data communications, industrial communication links, medical communications links, *etc.* In networking environments, fiber optics have traditionally been employed in the network core as long-haul backbones. More recently, fiber optic technologies have been implemented at the network edge, *e.g.*, in metropolitan area network ("MAN") and local area network ("LAN") environments. Examples of other environments in which optical communication technologies are being deployed include network operation centers, corporate network backbone, central offices, and edge/core aggregation points.

As optical communications have been implemented in edge environments, an increased need has developed for optical interconnect equipment that is capable of alleviating bandwidth bottlenecks by using increased port densities to provide more links at higher speeds within a constrained physical infrastructure. At the same time that service providers are attempting to deploy such higher bandwidth solutions, they face market constraints that increasingly make such solutions more difficult to implement, *e.g.*, reduced capital budgets, physical space limitations, HVAC (heating, ventilation, and

air conditioning) limitations, increasing power costs due to limited power grid capacity, *etc.*

Modern conventional optical communication infrastructures commonly employ 1310 nm-based optical transmission technology for short, immediate, and some long-range links, while more expensive 1550 nm-based technologies are generally reserved to implement longer-haul requirements, often using dense wavelength division multiplexing ("DWDM"). Single mode fiber 1310 nm optical technologies have been employed for short-reach ("SR") and intermediate-reach ("IR") links using the abundance of unused dark fiber available in existing network infrastructures, such as may be found in MAN infrastructures. In this regard, 1310 nm-based optical solutions are denser and more power efficient than 1550 nm-based DWDM solutions. Furthermore, it is less expensive to utilize a separate fiber and 1310 nm optics for transmission of an additional signal in an environment where the separate fiber is already installed and available.

However, despite the implementation of 1310 nm-based optical technologies, service providers still face the problem of how to deploy more 1310 nm interconnects at higher speed and lower cost per bit within the same or smaller physical space, and in a manner that takes advantage of reductions that have been achieved in integrated circuit scale. Smaller systems consume less floor space and power, enabling telecommunications companies to minimize lease expenses for equipment space. Shrinking system footprints also enable carriers to migrate to smaller facilities located nearer to users at the network edge. Optical connectors and associated optical modules have been developed in an attempt to respond to market needs. For example, 1310 nm fiber optic communication technology is now commonly implemented using small form factor ("SFF") connectors, which support two optical fibers within a connector width of approximately 0.55 inches. However, even with use of SFF connector technology, port density improvements have not kept pace with corresponding improvements in scale that have been achieved in integrated circuit design.

SUMMARY OF THE INVENTION

Disclosed herein are systems and methods for optical communication that employ parallel fiber optic arrays to couple together two or more optical communication modules via physically distinct and signal-independent optical communication paths in which each signal-independent optical communication path is capable of transporting one or more signals that are separate and independent from other optical communications paths. The disclosed systems and methods may be advantageously implemented to provide a much denser and more power efficient optical interconnect solution for high speed/multi-port optical systems than is available using conventional technology and, in doing so, may be implemented to allow system providers to overcome existing barriers to improvements in density, power efficiency and cost effectiveness. The physically distinct and signal-independent optical communication paths provided by the disclosed systems and methods also make possible increased flexibility in system architecture.

In one disclosed embodiment, parallel fiber optic connectors may be employed in combination with fiber optic arrays to enable much higher port densities and greater power efficiency than is possible using existing SFF-based devices. For example, commercially available parallel fiber optic connectors commonly employed in single point-to-point parallel ribbon fiber applications (*e.g.*, conventional MTP™ connectors that support up to 12 single-mode fibers in a single ferrule and connector) may be employed to provide separate signal-independent communication paths having transmission characteristics that meet the much more demanding standards required for single fiber single point-to-single point applications, *e.g.*, standards such as may be set by IEEE, ITU and ANSI standards bodies. Surprisingly, such single point-to-point connectors may be used in the disclosed systems and methods to provide multiple (*e.g.*, non-single point-to-single point) communication paths that are physically distinct and signal-independent from each other while also being standards-compliant for each path. In one embodiment, such connectors may also be employed in a manner to support or enable up to four times the number of ports on a card edge as compared to an alternative design based on small form factor devices.

In another disclosed embodiment, parallel fiber optic connectors may be employed in combination with vertical-cavity surface-emitting lasers ("VCSELs") to provide multiple signal-independent optical communication paths in a high density single mode configuration that offers smaller size and reduced power consumption at a lower cost than traditional SFF-based implementations. Using VCSELs enables multiple optical transmitters to be integrated into a single transmit module to which a parallel fiber optic connector, such as an MTP™ connector, may be coupled to provide an independent optical transmitter for each fiber optic port of an MTP™ connector array. In such an implementation, two or more 1310 nm-based transmit and receive array modules (*e.g.,* based on 1310 nm VCSEL technology) may be coupled together, for example, using MTP™ connectors in conjunction with industry standard single and/or duplex fiber connectors. When compared to conventional 1310 nm SFF-based transceivers, such an implementation may be used to realize system-level improvements such as increased system level densities, reduced power supplies, elimination of cooling fans, lower system costs, smaller system footprint for remote and/or space-restricted locations (*e.g.,* remotely located pedestals, distribution cabinets in a multi-tenant unit or corporate campus, elevated installations on utility poles, *etc.*), increased battery back up time for remote systems, and/or greatly simplified fiber management.

Thus, the disclosed systems and methods may be advantageously used to enable many more signal-independent optical ports to be integrated into a single optical communication system than is possible with existing optical communication technologies such as conventional SFF-based technology. Furthermore, benefits of lower cost per port and lower cost per bit may be realized using the disclosed systems and methods because the cost of supporting functions including power supplies, fans, printed circuit boards, and chassis may be spread across a larger number of ports.

Another benefit that may be additionally or alternatively realized using the disclosed systems and methods is simplification of the management of fiber optic cables attached to a optical communication system that includes one or more optical communication modules. For example, in one embodiment the bulk, weight, cost, and

complexity associated with fiber optic cabling may be greatly reduced by bundling multiple independent fibers into a single ribbon cable for coupling to an optical communication module. Individual fibers of a single ribbon cable may then be split apart or otherwise separated at a point removed from the optical communication system, *e.g.*, split out at a patch panel with a simple fan out cable assembly for routing to different locations.

In one respect, disclosed is a fiber optic communication assembly, including: an optical communication module having a plurality of at least three fiber optic ports, the plurality of fiber optic ports being configured as an array, at least a first one of the plurality of fiber optic ports being signal-independent from at least a second one of the fiber optic ports; and a plurality of fiber optic conductors each having a first end and a second end providing an optical communication path therebetween, each of the plurality of fiber optic conductors being coupled at its first end to one of the plurality of fiber optic ports, the first ends of the plurality of fiber optic conductors being disposed in adjacent parallel relationship at the plurality of fiber optic ports. A first one of the fiber optic conductors of the fiber optic communication assembly may be coupled to the first one of the plurality of fiber optic ports to form a first signal-independent optical communication path, and a second one of the plurality of fiber optic conductors may be coupled to the second one of the plurality of fiber optic ports to form a second signal independent optical communication path. The second end of the first fiber optic conductor may be configured to be disposed in remote physical relationship to the second end of the second fiber optic conductor.

In another respect, disclosed herein is an optical communication system, including: a first optical communication module having a plurality of at least three fiber optic ports, the plurality of fiber optic ports being configured as an array, at least a first one of the plurality of fiber optic ports being signal-independent from at least a second one of the fiber optic ports; and a plurality of fiber optic conductors each having a first end and a second end providing an optical communication path therebetween, each of the plurality of fiber optic conductors being coupled at its first end to one of the plurality of

fiber optic ports, the first ends of the plurality of fiber optic conductors being disposed in adjacent parallel relationship at the plurality of fiber optic ports. A first one of the fiber optic conductors of the optical communication system may be coupled to the first one of the plurality of fiber optic ports to form a first signal-independent optical communication path, and a second one of the plurality of fiber optic conductors may be coupled to the second one of the plurality of fiber optic ports to form a second signal independent optical communication path. The second end of the first fiber optic conductor may be coupled to a first fiber optic port of a second communication module to form the first signal-independent optical communication path between the first communication module and the second communication module. The second end of the second fiber optic conductor may be coupled to a first fiber optic port of a third communication module to form the second signal-independent optical communication path between the first communication module and the third communication module.

In another respect, disclosed is a method of optical communication, including providing an optical communication module having a plurality of at least three fiber optic ports, the plurality of fiber optic ports being configured as an array and being coupled to plurality of fiber optic conductors each having a first end and a second end providing an optical communication path therebetween, each of the plurality of fiber optic conductors being coupled at its first end to one of the plurality of fiber optic ports, the first ends of the plurality of fiber optic conductors being disposed in adjacent parallel relationship at the plurality of fiber optic ports, a first one of the fiber optic conductors being coupled to a first one of the plurality of fiber optic ports to form a first optical communication path, and a second one of the plurality of fiber optic conductors being coupled to a second one of the plurality of fiber optic ports to form a second optical communication path, the second end of the first fiber optic conductor being disposed in remote physical relationship to the second end of the second fiber optic conductor. The method of this embodiment may also include transmitting or receiving a first optical signal at the first fiber optic port of the first optical communication module through the first optical conductor, the first optical signal being signal-independent from an optical signal

transmitted or received at the second fiber optic port of the first optical communication module.

In another respect, disclosed herein is a fiber optic communication assembly, including: an optical communication module having a plurality of fiber optic ports, the plurality of fiber optic ports being configured as a single-wafer array, at least a first one of the plurality of fiber optic ports being signal-independent from at least a second one of the fiber optic ports; a plurality of fiber optic conductors each having a first end and a second end providing an optical communication path therebetween, each of the plurality of fiber optic conductors being coupled at its first end to one of the plurality of fiber optic ports, the first ends of the plurality of fiber optic conductors being disposed in adjacent parallel relationship at the plurality of fiber optic ports. A first one of the fiber optic conductors of the fiber optic communication assembly may be coupled to the first one of the plurality of fiber optic ports to form a first signal-independent optical communication path, and a second one of the plurality of fiber optic conductors may be coupled to the second one of the plurality of fiber optic ports to form a second signal independent optical communication path. The first signal-independent optical communication path may be physically distinct from the second signal-independent optical communication path.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a simplified representation of a fiber optic communication assembly according to one embodiment of the disclosed system and methods.

FIG. 2 illustrates optical signal variability as a function of distance for a fiber optic communication system employing conventional single point-to-point ribbon fiber cabling.

FIG. 3 illustrates optical signal variability as a function of distance for an optical communication system employing multiple signal-independent and physically distinct

optical communication paths according to one embodiment of the disclosed systems and methods.

FIG. 4 is a simplified representation of a fiber optic communications system according to one embodiment of the disclosed systems and methods.

FIG. 5A is a simplified representation of another fiber optic communications system according to one embodiment of the disclosed systems and methods.

FIG. 5B is a simplified representation of another fiber optic communications system according to one embodiment of the disclosed systems and methods.

FIG. 6 is a perspective view of a SONET fiber optic metro system based on conventional small form factor transceivers.

FIG. 7 is a perspective view of a SONET fiber optic metro system according to one embodiment of the disclosed systems and methods.

DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

FIG. 1 illustrates one embodiment of a fiber optic communication assembly **100** that includes an optical communication module **110** having multiple fiber optic ports **111** configured as an array **112**. Multiple fiber optic conductors **120** are shown optically coupled to each of the fiber optic ports **111** of array **112**. In this regard, a fiber optic conductor may be any combination of structure (*e.g.*, fiber, filament, rod, *etc.*) and material (*e.g.*, glass, plastic, *etc.*) suitable for conducting light waves from point to point. Although illustrated as a single segment in **FIG. 1**, each of fiber optic conductors **120** may include one or more individual fiber optic segments, optical connectors and/or other optical coupling devices coupled between its respective first end **122** and second end **124**.

As shown in **FIG. 1**, multiple fiber optic conductors **120** extend from array **112** in adjacent parallel relationship (*i.e.*, extending from array **112** in parallel or substantially parallel manner), and then diverge or otherwise separate so that each of multiple fiber optic conductors **120** defines an optical communication path that is physically distinct, *i.e.*, they are no longer disposed in adjacent parallel relationship with other fiber optic conductors **120** (*e.g.*, not bundled together or disposed in a ribbon fashion), and/or have lengths or paths that differ from other fiber optic conductors **120**. It will be understood that each of fiber optic conductors **120** may include one or more individual fiber optic segments, connectors and/or other optical coupling devices disposed between its respective first end **122** and second end **124**. A physically distinct optical communication path may also be defined by a fiber optic conductor **120** having a different physical configuration than other fiber optic conductors **120** (*e.g.*, having differing number or type of fiber optic segments, having differing number or type of connectors, having a passive module connected at second end **124** for splitting out multiple wavelengths, *etc.*), although this characteristic need not necessarily be present. In this regard, a fiber optic conductor **120** may be optionally configured in one exemplary embodiment to communicate a plurality of optical signals (*e.g.*, using wavelength division multiplexing (WDM), coarse WDM, DWDM, *etc.*), and may include a splitter and/or combiner at first end **122** and/or second end **124** as appropriate to split or combine a plurality of wavelengths for communication to or from given fiber optic ports of an array **112**.

As further illustrated in **FIG. 1**, second ends **124** of multiple fiber optic conductors **120** may also be disposed in a variety of physically separate remote locations (*e.g.*, terminating in a manner that is other than adjacent and parallel). Examples of physically remote locations at which two or more fiber optic conductors **120** may terminate include, but are not limited to, non-adjacent fiber optic port locations on a common optical communication module or chassis, locations on different modules or chassis in the same room or facility, locations in different rooms or facilities in the same building, locations in different buildings, locations in different cities or towns, locations in different telephone company central office buildings, *etc.*). Fiber optic communication assembly **100** may be implemented alone or with other fiber optic communication

assemblies for optical coupling purposes in a variety of different applications including, but not limited to, to make connections between two or more fiber optic arrays, to make backplane interconnections between multiple system modules, to make chassis-to-chassis interconnections, to make connections for arrays to single channel or multiple channel transmitters, receivers or transceivers, *etc.*

Still referring to the embodiment of **FIG. 1**, optical communication module **110** may be any optical communication device having multiple fiber optic ports **111** configured in a fiber optic array **112** that is capable of transmitting and/or receiving at least one signal-independent optical signal (*e.g.,* single mode optical signal, multiple mode optical signal, *etc.*) in one of the fiber optic ports **111** of array **112**. In this regard, a given fiber optic port **111** may be capable of transmitting or receiving an optical signal through a fiber optic conductor **120** that is independent (*e.g.,* separate and different) from an optical signal that is simultaneously transmitted or received through another fiber optic conductor **120** by another fiber optic port **111** in the same fiber optic array **112** (*e.g.,* using multiple independent transmitters and/or receivers coupled to the same array **112**). For example, one fiber optic port **111** may transmit a signal that is independent and separate from a signal transmitted by another fiber optic port **111**, and/or one fiber optic port **111** may transmit a signal while another fiber optic port **111** in the same array **112** may receive a separate and independent signal. It is possible that any one or more individual fiber optic ports **111** of a fiber optic array **112** may be characterized as signal-independent, and that a signal-independent fiber optic port may be coupled to a respective fiber optic conductor **120** to form a signal-independent optical communication path. In one exemplary embodiment, each fiber optic port **111** of fiber optic array **112** may be characterized as being signal-independent from all other fiber optic ports **111** in the same array **112**, and multiple fiber optic ports **111** may be coupled to respective multiple fiber optic conductors **120** to form multiple signal-independent optical communication paths.

In the exemplary embodiment illustrated in **FIG. 1**, fiber optic array **112** is shown having 12 fiber optic ports **111** and as being configured in a 1x12 rectangular array. However, it will be understood that various other array configurations may be employed

having multiple fiber optic ports configured to be coupled to multiple fiber optic conductors in adjacent parallel relationship. In one embodiment, a fiber optic array of an optical communication module may be characterized as having at least two fiber optic ports configured in an adjacent disposed relationship, alternatively as having at least three fiber optic ports configured in an adjacent disposed relationship, and further alternatively as having at least four fiber optic ports configured in an adjacent disposed relationship. Such an array may be of any suitable array geometry, as necessary or desirable for a given application (*e.g.*, rectangular array, square array, circular array, irregular array, *etc.*). A rectangular or square fiber optic array may be configured with one or more columns and one or more rows. Examples of suitable types of rectangular or square arrays include, but are not limited to, single row arrays (*e.g.*, 1 x 4, 1 x 8, 1 x 12, *etc.*), single column arrays, and general two dimensional arrays (*e.g.*, 2 x 4, 2 x 8, 2 x 12, 6 x 12, *etc.*).

In the practice of the disclosed systems and methods, a fiber optic array may be configured in any density suitable for use with fiber optic conductors to form physically distinct and signal-independent optical communication paths in a manner such as described elsewhere herein. In one exemplary embodiment, a fiber optic array may be configured to have a density of less than about 0.4 inch per port, alternatively to have a density of less than about 0.3 inch per port, alternatively to have a density of less than about 0.2 inch per port, and further alternatively to have a density of about 0.1 inch per port. In another exemplary embodiment, a fiber optic array may be configured to have a density of less than about 0.1 inch per port, alternatively less than about 0.05 inch per port, and further alternatively to have a density of about 0.02 inch per port. It will be understood with benefit of this disclosure that a given density may be achieved using fiber optic arrays suitably dimensioned to achieve the given density, for example, by employing single wafer arrays (*e.g.*, having multiple lasers formed on the same die, or one continuous wafer with multiple lasers disposed on it), although other types of arrays may be employed in other embodiments (*e.g.*, having multiple laser packages at the die level and incorporated into a module).

As previously mentioned, optical communication module **110** may include an optical transmitter array, an optical receiver array, or a combination thereof (*e.g.*, optical transceiver array) that has one or more signal-independent fiber optic ports **111**. In this regard, any optical communication device having a fiber optic array suitable for signal-independent operation in one or more fiber optic ports may be employed as optical communication module **110**. Exemplary types of optical communication devices that may be employed as optical communication module **110** include, but are not limited to, vertical-cavity surface-emitting laser (VCSEL) fiber optic arrays, edge-emitting laser-based fiber optic arrays, PIN photo diode detector arrays, avalanche photo diode detector arrays, LED-emitting diode fiber optic arrays, *etc.* Examples of suitable VCSEL fiber optic arrays that may be employed include, but are not limited to, 850-nm VCSEL arrays, 1310 nm VCSEL arrays, 1550 nm VCSEL arrays, *etc.* Other examples of suitable VCSEL fiber optic arrays that may be employed include, but are not limited to, VCSEL fiber optic arrays having a wavelength in the range of from about 1260nm to about 1660nm, although VCSEL fiber optic arrays having wavelengths of greater than about 1660nm or less than about 1260nm may also be suitably employed. In one exemplary embodiment, optical communication module **110** may be a 12-channel 1310 nm transmit array module or 12-channel 1310 nm receive array module. Further information on suitable VCSEL fiber optic array technology may be found described in United States Provisional Patent Application Serial No. 60/___________ (Attorney Docket No. CLO166.2), filed February 8, 2002, and entitled "Long Wavelength Vertical Cavity Surface Emitting Laser" by Naone et al., the disclosure of which is incorporated herein by reference.

Fiber optic conductors **120** may be provided together (*e.g.*, packaged, laid out, arranged, bundled, *etc.*) at first end **122** in any manner suitable for orienting conductors **120** in adjacent parallel relationship for coupling with respective fiber optic ports **111**. In one embodiment, fiber optic conductors **120** may be provided together at first end **122** as a parallel ribbon cable. In such an embodiment, any type of parallel ribbon cable may be employed that is suitable for coupling multiple fiber optic conductors to a corresponding suitable fiber optic array in a manner as described herein. Suitable parallel ribbon cables

may be configured with any suitable number of individual fiber optic conductors to meet a given application and/or may be available from a variety of sources. Specific examples of suitable parallel ribbon cables include, but are not limited to, MTP™/MPO, MPX, SMC™, *etc.*

In the practice of the disclosed systems and methods, individual fiber optic conductors **120** may be provided together at first end **122** with a multiple fiber connector suitable for interconnection with a corresponding mating multiple fiber connector on optical communication device **110** so as to allow simultaneous coupling of individual fiber optic conductors **120** with respective individual fiber optic ports **111** (*e.g.*, to connect an entire array **112** directly to a fiber ribbon cable). Specific examples of suitable multiple fiber connectors that may be employed for interconnection of multiple fiber optic conductors **120** to multiple fiber optic ports of array **112** include, but are not limited to, high density MTP™ connectors available from U.S. Connec of Hickory, North Carolina, MPX connectors, MPO connectors, SMC™ connectors, VF-45 connectors, *etc.* However, it will be understood that in other embodiments one or more of multiple fiber optic conductors **120** may be coupled to respective multiple fiber optic ports of fiber optic array **112** using other suitable type of connectors or using no connectors (*e.g.*, conductors spliced directly into the ports). Furthermore, it is not necessary that multiple fiber optic conductors **120** be provided in the form of a parallel ribbon cable at first end **122** for connection to optical communication module **110**, but instead may be provided as individual fiber optic conductors that are separately coupled to the fiber optic ports of array **112**.

In one exemplary embodiment employing fiber ribbon cable and MTP™ connectors, chassis-to-chassis coupling may be achieved using a direct fiber ribbon cable link with MTP™ connectors on both chassis ends to deliver one or more independent optical signals between two chassis components. Alternatively, the illustrated embodiment may be advantageously employed to achieve a wide variety of system configurations, *e.g.*, to efficiently connect fiber optic arrays into existing fiber infrastructures, by employing ribbon cables that fan out from a single MTP™ interface of

an optical communication module **110** into individual (*e.g.*, LC, SC, FC, *etc.*) connectors at a patch panel (*e.g.*, at front-side or back-side side of patch panel). In the latter embodiment, one or more independent optical signals may be delivered from a first optical communication module **110** to two or more other separate optical modules (not shown in **FIG. 1**), as in a manner that will be described further herein.

As previously described, for embodiments such as those illustrated in **FIG. 1**, one or more optical ports of array **112** of optical communication module **110** may be signal-independent. For example, optical communication module **110** may be configured so that at least a portion the optical ports of fiber optic array **112** are each signal-independent and coupled to its own separate transmit laser or separate photodetector for transmitting or receiving a separate optical signal through a respectively coupled fiber optic conductor **120**. In such an implementation, one or more control signals may be provided to facilitate signal independent operation for each of respective optical fiber optic ports of array **112**. For example, a transmit disable (Tx_Disable) signal may be employed on one or more transmitting ports of array **112** to disable faulty or defective individual transmitters, without affecting other properly operating transmitters coupled to other ports of array **112**. It will be understood that such a Tx_Disable signal may be employed by an optical communication module **110** that is configured as optical communication transmitter module, or that is configured as an optical transceiver module in order to control operation of individual transmit lasers employed therein. Similarly, a loss of signal (LOS) control signal may be employed on each receiving port of array **112** of an optical communication module **110** (e.g., optical receiving module, optical transceiving module) to facilitate independent operations of each signal independent optical communication path through an associated fiber optic conductor **120**.

In one embodiment of the disclosed systems and methods, it is possible to further facilitate signal-independent operation of one or more optical communication paths by enhancing channel isolation so as to reduce cross talk that may occur between individual fiber optic conductors **120** (*e.g.*, caused by spill-over light from a laser into an adjacent fiber not directly coupled to that laser). This may be particularly desirable in those

embodiments where one or more fiber optic conductors **120** vary in length from one or more other fiber optic conductors **120** coupled to the same fiber optic array **112**, and/or where one or more fiber optic conductors **120** have second ends **124** that terminate in a location physically remote from the second ends **124** of other fiber optic conductors **120.** Under such conditions, adverse effects such as cross talk may be exacerbated by greatly increased attenuation of an incoming optical signal at a fiber optic receiving port **111** of an optical communications module **110** coupled to an fiber optic conductor **120**. In this regard, incoming signal variability experienced by a single optical communication module **110** between two or more fiber optic conductors **120** that define physically distinct optical communication paths (*e.g.*, having independent signals originating at physically remote locations, having different lengths, *etc.*) is typically greater than the incoming signal variability experienced between multiple fiber optic conductors having the same length and that are routed in adjacent parallel relationship along their entire lengths, *e.g.*, such as a fiber ribbon cable used in a conventional single-point-to-single point application employing a single high bandwidth transmitter and single high bandwidth receiver.

FIG. 2 and **FIG. 3** are representations of signal variability for multiple fiber optic conductors as a function of distance between fiber optic transmission ports and fiber optic receiver ports. In this regard, **FIG. 2** represents signal variability experienced between individual fiber optic conductors that are arranged in adjacent parallel relationship (*e.g.*, ribbon fiber cable) for single-point-to-single point optical communication, *e.g.*, from fiber optic transmission ports of the same fiber optic array to fiber optic receive ports of the same fiber optic array. In contrast, **FIG. 3** represents signal variability experienced between individual fiber optic conductors that define physically distinct and signal independent optical communication paths, such as for multiple-point-to-single point optical communication, *e.g.*, from multiple fiber optic transmission ports positioned at physically remote second ends **124** through fiber optic conductors **120** to fiber optic receive ports **111** of optical communication module **110**.

As may be seen by comparing **FIG. 2** with **FIG. 3**, fiber attenuation variability (B) is much greater between individual fiber conductors that define physically distinct optical communication paths than it is between individual parallel conductors of a single-point-to-single point ribbon fiber cable configuration, resulting in a much greater variability in incoming optical signal strength (C) between different optical communication paths as experienced by a given optical communication module of a multiple-point-to-single point optical communication path configuration. It may also be seen from **FIGS. 2** and **3** that maximum fiber attenuation and signal variability increases with distance between fiber optic transmission and receive ports, making the task of configuring a given optical communication module to accept such widely variable signals in a standards-compliant manner more difficult with increasing length of optical communication paths. Although illustrated with respect to distance, it will be understood that increases in signal variability may additionally or alternatively result from differing number and quality of optical conductors and/or connectors that are employed to define one or more optical communication paths of a given system.

In one embodiment of the disclosed systems and methods, a fiber optic communication assembly **100** may be further configured to provide one or more standards-compliant optical communication paths using any system configuration in which optical signals may be transmitted and/or received across optical conductors and, in one exemplary embodiment, may be configured to provide standards compliance under signal variability conditions described and illustrated in relation to **FIG. 3.** In one example, the disclosed systems and methods may be implemented to enable optical communication module **110** to transmit and/or receive optical communication signals through optical conductors **120** that are compliant to signal-independent optical communication standards, *e.g.,* as may be established by standards bodies such as the IEEE, ITU or ANSI standards groups. Specific examples of such signal-independent standards include, but are not limited to, IEEE 802.3z Gigabit Ethernet 1000 BASE-LX Standards, SONET Short-reach OC-1 through OC-48 standards, Telcordia Technologies GR-253 CoreSONET standards, ANSI T1, ESCON, *etc.* Such standards-compliant optical communication paths may be enabled, for example, by using any suitable optical

communication module **110** or combination of multiple optical communication modules **110** that is capable of achieving channel isolation and reduction in cross talk sufficient to achieve optical bit error rate ("BER") design objectives necessary to meet a given standard (*e.g.,* despite wide incoming signal variability that may be experienced in system configuration as described and illustrated in relation to **FIG. 3**).

In one embodiment of the disclosed systems and methods, pairs of VCSEL fiber optic transmit and PIN photodiode detector receive ports may be employed to support signal compliance of independent incoming signals from multiple and physically distinct optical communication paths that exhibit a relatively large difference in signal variability by enhancing channel isolation so as to reduce cross talk and preserve independent signal integrity. For example, signal-independent and standards-compliant optical communication paths through optical conductors **120** may be enabled by configuring an optical communication module **110** with a single mode VCSEL having spatially varying optical loss to provide single-mode operation, such as described in United States Patent Application Serial No. 09/587,074, filed June 2, 2000, and entitled "Single Mode Vertical Cavity Surface Emitting Laser" by Scott et. al., the disclosure of which is incorporated herein by reference. Such a single mode VCSEL may be implemented, for example, as part of a standards-compliant optical communication transmitter module having a self-adjusting data transmitter driver that is capable of monitoring characteristics of an optical data signal and that is further capable of using feedback (*e.g.,* based on parameters such as BER, data eye, discreet optical data integrity parameters, and discreet optical parameters) to adjust the optical quality of the laser output towards optimization in order to meet standards compliance. Such a self-adjusting data transmitter driver is described in United States Patent Application Serial No. 10/___________ (Attorney Docket No. CLO123), filed December 20, 2001, and entitled "Self-Adjusting Data Transmitter" by Yorks, the disclosure of which is incorporated herein by reference.

Alternatively, a photodetector may be implemented as part of a standards-compliant optical communication receiver module having an opto-electronic device configured as a photo detector and having an on-chip capacitor design that utilizes

combinations of capacitors and resistors to reduce cross talk among adjacent detectors in fiber optic arrays. Such a technology is described in United States Patent Application Serial No. 10/____________ (Attorney Docket No. CLO155), filed November 30, 2001, and entitled "High Speed Detectors Having Integrated Electrical Components" by Lindemann et al., the disclosure of which is incorporated herein by reference.

FIG. 4 illustrates one exemplary embodiment of an optical communication system **400** having an optical communication transmitter module **410** in optical signal communication with an optical communication receiver module **420** via at least one optical conductor **402** providing a signal-independent optical communication path therebetween. As illustrated in **FIG. 4**, optical communication transmitter module **410** is provided with "m" number of multiple transmitter input signals **404**, each of which corresponds to a separate signal independent fiber optic transmitter port of fiber optic array **408** of optical communication transmitter module **410**. A multiple fiber connector **406** is provided for connecting individual optical conductors **402** in adjacent parallel relationship to respective signal-independent fiber optic ports (not shown) of array **408**. Similarly, multiple optical conductors **402** are coupled to respective signal independent fiber optic ports (not shown) of fiber optic array **418** of optical communication receiver module **420** using multiple fiber connector **416**. An "n" number of multiple receiver output signals **414** corresponding to respective signal-independent fiber optic ports of array **418** are provided for optical communication receiver module **420** as illustrated.

Although **FIG. 4** illustrates an optical communication transmitter module **410** coupled to an optical communication receiver module **420** via at least one optical conductor **402**, it will be understood that either one or both of optical communication modules **410** and **420** may be optical transceiver modules, *e.g.*, with a fiber optic transmitter port of transceiver module **410** coupled to a fiber optic receiver port of transceiver module **420**. Further, it will be understood that modules **410** and **420** may be coupled together with two or more optical conductors **402** in a manner similar as illustrated for at least one optical conductor of **FIG. 4**. In such a case, it will be

understood that any two or more optical communication paths may be physically distinct from each other even though they are coupled between the same two modules.

In the embodiment illustrated in **FIG. 4**, any desired number of optical conductors **402** may be coupled to fiber optic array ports of optical communication transmitter module **410** and/or optical communication receiver module **420**. Furthermore, it will be understood it is possible that a number of optical conductors **402** (e.g., 12) may be coupled to fiber optic array ports of optical communication transmitter module **410** that differs from the number of optical conductors **402** (e.g., 8) coupled to fiber optic array ports of optical communications receiver module **420**. This may result, for example, where optical communication transmitter module **410** is provided with a different number of fiber optic array ports than is optical communication receiver module **420**, and/or when not all fiber optic array ports of one or both modules are coupled to a respective optical conductor **402** (*i.e.*, not all fiber optic ports of a given module array need be used or coupled to an optical conductor, nor do all optical conductors of a given multiple fiber connector need be used or coupled to a fiber optic port). Furthermore, as will be illustrated and described further herein, it is also possible that only one of optical communication modules **410** and **420** may be configured with an array of multiple signal-independent fiber optic ports, with the other module being alternatively configured to have a single signal-independent fiber optic port coupled to a optical conductor **402** via a single fiber connector, *e.g.*, LC connector, SC connector, FC connector, directly connected to an optical transmitter or receiver through splices, etc.

In the embodiment illustrated in **FIG. 4** intermediate fiber connectors **430** are illustrated as being present within each of the optical communication paths defined by optical conductors **402**. It will be understood that intermediate fiber connectors **430** are optional and may not be present in any given optical communication path defined by an optical conductor **402**, and/or that more than two intermediate fiber connectors **430** may be present in any given optical communication path defined by an optical conductor **402**. Intermediate fiber conductors may be any type of connector suitable for coupling two or more fiber optic segments together, alone or in parallel with other fiber optic segments.

Examples of intermediate fiber connectors include, but are not limited to, patch panel connector, bulkhead feedthroughs, optical cross connects, switches, *etc.* In one exemplary embodiment, an intermediate fiber connector **430** may be a patch panel that facilitates distribution or separation of optic conductors **120**, *e.g.* transitioning from a parallel ribbon fiber cable configuration to a distributed and physically distinct separate fiber configuration.

Further illustrated in **FIG. 4** are "m" number of Tx_Disable control signals (e.g., one for each independent signal transmitted by optical communication transmitter module **410**). Similarly shown are "n" number of LOS control signals (*e.g.,* one for each independent signal received by optical communication receiver module **420**). These control signals may be advantageously employed in a manner as previously described to facilitate signal-independent operation for each of the signal-independent fiber optic ports of arrays **408** and **418,** and their associated signal-independent optical communication paths defined by optical conductors **402**.

FIG. 5A illustrates an exemplary fiber optic communication system **500** that includes multiple optical communication transmitter modules (*i.e.*, **510**, **512**, and **514**) and multiple optical communication receiver modules (*i.e.*, **520**, **522**, and **524**) coupled together by multiple signal independent optical conductors **502**. It will be understood that the system configuration illustrated in **FIG. 5A** is exemplary only, and is illustrative of the types of fiber optic system configurations that may be present in a given embodiment of the disclosed systems and methods. For example, it will be understood that any combination of two or more of the optical communication transmitter modules and optical communication receiver modules illustrated in **FIG. 5A** may be employed separately or in combination with other optical communication modules as desired to achieve a desired system configuration. Furthermore, it will be understood that any one or more of modules **510**, **512**, **514**, **520**, **522**, and/or **524** may be optical communication transceiver modules (*e.g.,* one or more separate receiver modules and/or transmitter modules coupled to transceiver module, one or more transceiver modules coupled to other transceiver modules, *etc.*).

As illustrated in **FIG. 5A**, two or more optical communication transmitter modules (e.g., **510** and **512**) having the same or different number of signal-independent fiber optic transmit ports may be coupled to two or more optical communication receiver modules (e.g., **522** and **524**) having the same or different number of signal-independent fiber optic receiver ports, via one or more signal-independent optical communication paths defined by optical conductors **502** coupled between each given pair of coupled optical communication modules. Furthermore, an optical communication transmitter module **510** having multiple signal-independent fiber optic ports may be coupled to an optical communication receiver module **520** having a single fiber optic detector port. Likewise, an optical communication transmitter module **514** having a single fiber optic transmit port may be coupled to an optical communication receiver module **522** having multiple signal-independent fiber optic ports.

Not shown in **FIG. 5A** are other optical communication modules that may be coupled, for example, to optical communication transmitter module **510** and optical communication receiver module **524** via signal-independent optical communication paths defined by optical conductors **504**. It will also be understood with regard to **FIG. 5A** that it is possible that instead of being single fiber optic port modules, optical communication transmitter module **514** and/or optical communication receiver module **520** may alternatively be optical communication modules having multiple signal-independent fiber optic ports, but to which only one optical conductor **502** is coupled.

In the embodiment of **FIG. 5A**, any suitable optical conductor configuration as previously described herein may be employed to couple two respective optical communication modules (*e.g.*, optical communication transmitter module to optical communication receiver module, optical communication transmitter module to optical transceiver module, optical communication receiver module to optical transceiver module, optical transceiver module to optical transceiver module). In this regard, each optical conductor may define an optical communication path including one or more optical conductor segments that may or may not be interconnected by one or more fiber

optic connectors. Furthermore, each optical conductor may be coupled to a given optical communication module via a connector (e.g., multiple fiber connector or single fiber connector as appropriate) or may be hardwired or spliced directly to fiber optic ports of a given optical communication module.

FIG. 5B illustrates another exemplary fiber optic communication system **500** that includes multiple optical communication transmitter modules (*i.e.*, **510**, **512**, and **514**) and multiple optical communication receiver modules (*i.e.*, **520**, **522**, and **524**) coupled together by multiple signal independent optical conductors **502** having intermediate fiber connectors **530** that may include, for example, one or more patch panels that facilitate distribution or separation of optic conductors **120** in a manner as previously described.

The disclosed systems and methods described and illustrated herein may be employed as part of any optical communication system that is utilized to transmit and/or receive two or more signal-independent optical signals between at least two optical communication modules. Examples of types of implementation environments in which disclosed systems and methods may be employed include, but are not limited to, network applications (*e.g.*, LAN, MAN, WAN SAN, etc.), switch applications (*e.g.*, digital SONET, Ethernet, Fibre Channel, industrial control lines, internal and/or external optical interconnects in entertainment equipment systems, *etc.*). Specific examples of network applications in which the disclosed systems and methods may be employed include, but are not limited to, in the last mile network of a metropolitan area network, in a high speed hub and spoke distribution system (*e.g.*, network, data center, or intersystem communication architecture), in a local area network, in a tree-structure network, *etc.* Specific examples of switch applications in which the disclosed systems and methods may be employed include, but are not limited to, in digital cross-connect switches, SONET drop multiplexors, Ethernet switches, IP routers, dense wavelength division multiplexing transport equipment, multi-service protocol provisioning platforms, Fibre Channel switches, aggregation equipment, Optical cross connect, *etc.*

FIG. 6 illustrates one example of a Synchronous Optical Network ("SONET") metro system **600** based on conventional SFF transceivers **610** mounted on the edges of multiple cards **620** of each of system components **602** and **604** of system **600**. As illustrated in **FIG. 1**, each SFF transceiver **610** is coupled to a respective two-fiber cable **612**. Each SFF transceiver has a separate transmitter and receiver corresponding to each of the two respective fibers within each cable **612**. Thus, as illustrated in **FIG. 6**, a total of 16 SFF transceivers **610** provided by two system components **602** and **604** are required to provide 32 separate optical communication paths per card **620** (*i.e.*, 16 separate transmit paths and 16 separate receive paths).

FIG. 7 illustrates a SONET metro system based on 1310 nm VCSEL fiber optic array modules **710** according to one embodiment of the disclosed system and methods. As shown in **FIG. 7**, four fiber optic array modules **710** are provided that interconnect with four fiber optic MTP™ connectors **712** at the edges of multiple cards **720** of component **702** of system **700**. Parallel fiber optic connectors **712** are in turn shown interconnected to parallel fiber optic ribbon cables **714**, which serve to couple system **700** to other optical communication modules or systems (not shown). A jumper cable **716** is shown provided on each card to interconnect each fiber optic array module **710** with a respective fiber optic MTP™ connector **712**. However, it will be understood that a module **710** may be alternatively mounted on the edge of a card **720**, *e.g.*, for direct interconnection with a respective fiber optic MTP™ connector **712**, so that a jumper cable **716** is not required.

In one exemplary implementation of **FIG. 7**, each fiber optic array module **710** may be configured with eight fiber optic ports, and cables **712** and **714** may each have eight fiber optic conductors. In one embodiment, two fiber optic array modules may be configured as optical communication transmitter modules and two fiber optic array modules may be configured as optical communication receiver modules. As so configured, the embodiment illustrated in **FIG. 7** is capable of providing 32 separate signal-independent optical communication paths (*i.e.*, 16 separate transmit paths and 16 separate receive paths) per card **720** from one system component **702**, eliminating the

need for an extra system component and its associated hardware and power needs (*e.g.*, power supplies, cooling fans, *etc.*) required by conventional system **600**. Furthermore, a visual comparison of conventional system **600** of **FIG. 6** with system **700** of **FIG. 7** illustrates the greatly improved density and smaller overall system size possible with implementations of the disclosed systems and methods. Thus, **FIG. 7** illustrates the significant advantages that may be achieved using one embodiment of the disclosed systems and methods over conventional SONET metro systems based on SFF transceivers. It will be understood that the embodiment of **FIG. 7** is exemplary only, and that further increases in density and/or reduction in size are possible, for example, by configuring fiber optic array module **710** to have more than eight fiber optic ports (*e.g.*, 12 or more fiber optic ports), and by configuring each of cables **712** and **714** with a number of fiber optic conductors (*e.g.*, 12 or more fiber optic conductors) corresponding to the number of fiber optic ports.

While the invention may be adaptable to various modifications and alternative forms, specific embodiments have been shown by way of example and described herein. However, it should be understood that the invention is not intended to be limited to the particular forms disclosed. Rather, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the appended claims. Moreover, the different aspects of the disclosed apparatus, systems and methods may be utilized in various combinations and/or independently. Thus the invention is not limited to only those combinations shown herein, but rather may include other combinations.